Case Study #1. Barnett Shale: The Start of the Gas Shale Revolution

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Presentation Outline

1. Introduction and Status
2. Historical Perspective
3. “Game Changer” Insights
4. Overview of Exploration, Reservoir Characterization and Development
5. Assessing Improving Well Performance
6. Lessons Learned
7. Concluding Thoughts

1. Introduction and Status

Introduction and Status

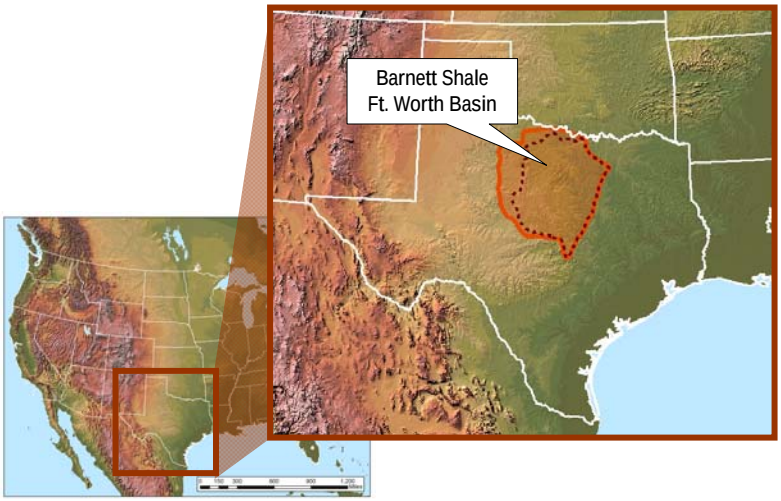
The “gold standard” of gas shale development is the Barnett Shale, Fort Worth Basin of North Texas.

The Barnett Shale gas play introduced the wide-scale use of intensively stimulated (hydraulically fractured) horizontal wells which have enabled deep gas shales to become economically productive.

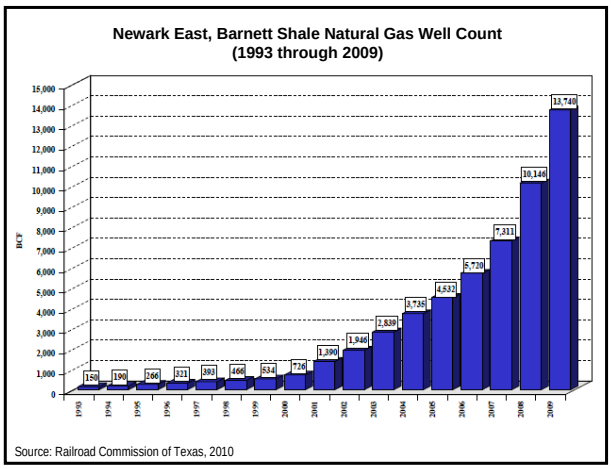
The Barnett Shale (Newark East field) has already produced 7 Tcf from nearly 14,000 wells.

With daily production of over 5 Bcf per day, the Barnett Shale/Newark East is today the largest natural gas field in the U.S.

Location of the Barnett Shale in North Texas



Introduction and Status



Source: Railroad Commission of Texas, 2010

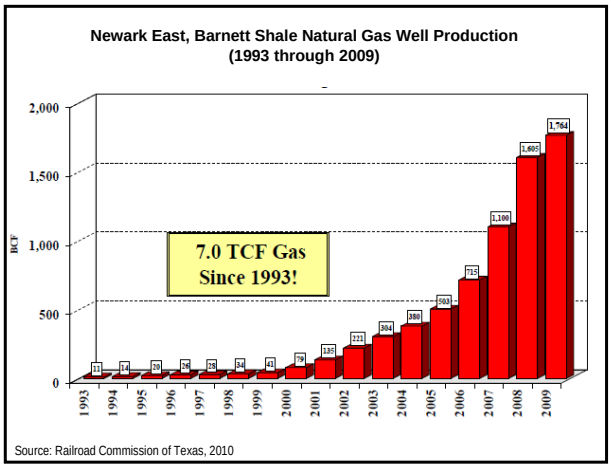
Initially, the Barnett Shale was developed with vertical wells.

Horizontal wells were introduced in 2002 and have become the dominant well design choice.

Barnett Shale Core Area		
	Vertical* Wells	Horizontal* Wells
'90-'95	215	1
'96-'00	500	3
'01-'03	2,001	76
'04-'06	904	1,008
'07-'08	131	1,810

*Successful wells

Introduction and Status



Source: Railroad Commission of Texas, 2010

Gas production from the Barnett Shale has gown rapidly in recent years.

	Annual Production	
	Tcf/Year	Bcfd
2004	0.4	1.0
2005	0.5	1.4
2006	0.7	2.0
2007	1.1	3.0
2008	1.6	4.4
2009	1.8	4.8

Additional production is from associated gas from Barnett Shale oil wells.

Introduction and Status

Reservoir Properties: Barnett Shale

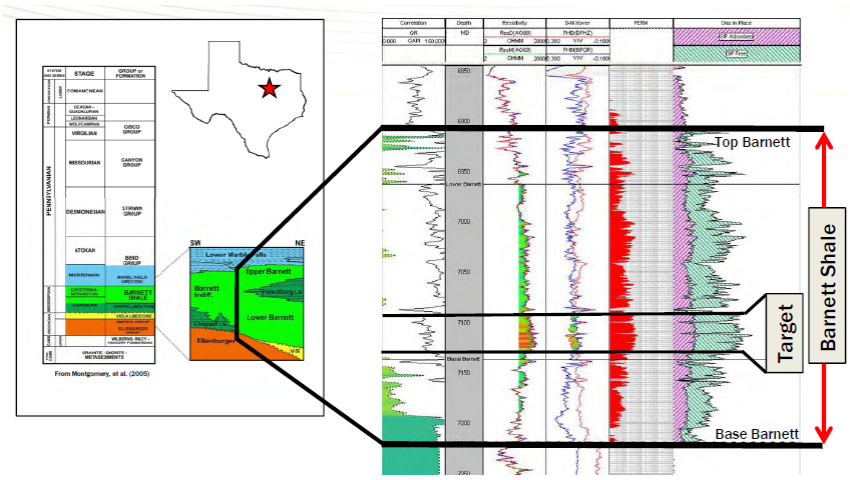
Depth	7,500'
• Gross Thickness	430'
• Net Thickness	390'
Porosity	6%
Pressure	3,500 psi
Total Gas In-Place (Bcf/mi^2)	$\pm$150
• Adsorbed Gas (Bcf/mi^2)	60
• "Free" (Porosity) Gas (Bcf/mi^2)	90

The Barnett Shale was the first deep gas shale (7,000 to 8,000 feet deep) to be commercially developed.

The gas shale is in two intervals, a thick, rich Lower Barnett and a leaner Upper Barnett.

The gas in-place, in the Core Area is $\pm$150 Bcf/mi^2, with about 40% from adsorbed gas and 60% from "free" gas.

Introduction and Status



Geologic and reservoir assessments are used to target horizontal wells into the rich, brittle interval of the shale.

Source: Chesapeake Energy

2. Historical Perspective

Historical Perspective

The U.S has been producing natural gas from shallow, organically rich fractured shales for many decades, including:

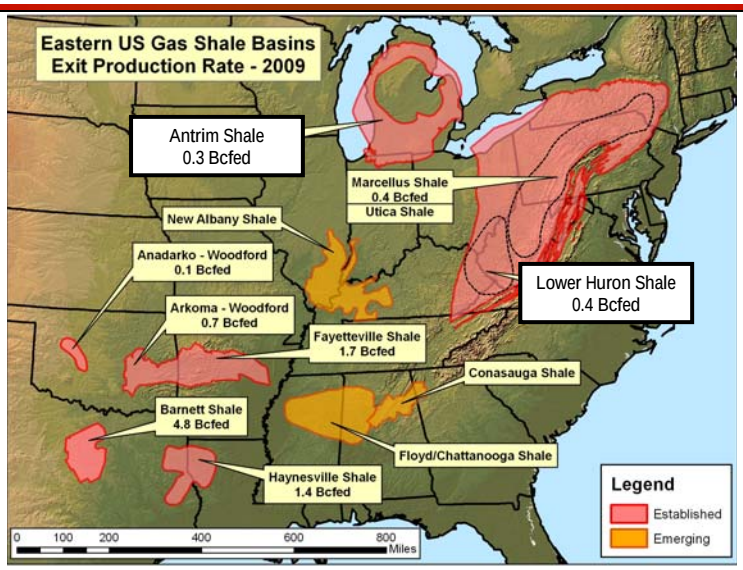
- The underpressured Huron (Devonian) Shale, Appalachian Basin.
- The "wet" Antrim Shale, Michigan Basin

Natural fractures were considered to be essential for flow rates. Adsorbed gas was the dominant gas storage mechanism. The clays in "dry" shales were thought to be water sensitive.

These shallow, 1,000 to 3,000 feet, shales were developed with low cost vertical wells and small fracs.

Gas production rates were modest but long lasting. Typical gas rates were 100 to 200 Mcf per day per well, with reserves of 0.25 Bcf to 0.5 Bcf per well.

Eastern U.S. Gas Shale Basins



Source: Advanced Resources International

Historical Perspective

Deep gas shales, such as the Marcellus Shale in the Appalachian Basin were known to exist. However, except for areas with intense natural fractures, the deep shales (much like deep coals) were considered to have essentially no permeability.

The early drilling results from the Barnett Shale, including Mitchell Energy's 1981 discovery well - - the C.W. Slay No. 1, tended to validate the conventional wisdom of "essentially no permeability" in deep shales.

- The C.W. Slay #1 well had a modest initial production rate of 120 Mcfd after cleanup.
- The initial vertically drilled wells had low EUR's of about 0.4 Bcf/well, not much different than the shallow (and much cheaper to drill) Huron and Antrim Shale wells.

Historical Perspective

For the next twenty years, the Barnett Shale operator, Mitchell Energy, continued experimenting with larger fracture designs, more rigorous reservoir characterization and lower cost well drilling and stimulation.

This formal process of "learning" helped double the productivity of the Barnett Shale vertical wells, making the play economic.

The recognition that gas shales contained a major second gas storage mechanism (porosity) and that one could create the essential flow paths in a deep shale reservoir with intensively fractured horizontal wells "changed the game".

But, I am getting ahead of myself.

3. "Game Changer" Insights

"Game Changer" Insights and Actions

A series of actions and insights "changed the game" for the Barnett Shale.

The 1998 *Oil and Gas Journal* article (Kuuskraa, et al, 1998) provided a very different interpretation of the Barnett Shale than accepted as the "conventional wisdom". The article stated that:

- In addition to adsorbed gas, porosity is a key gas storage mechanism in deep shales.
- The vertical wells were draining only a small area, 10 to 30 acres, not large 320 acre areas.
- The gas resource concentration was rich and the size of the Barnett Shale play was large, at least 10 Tcf.

Mitchell Energy recognized that higher injected energy was beneficial and that the Barnett Shale was not water sensitive. It began to use lower cost, large volume "slick water" low proppant concentration fracs.

Game Changing Insights and Actions

The final "game chancing" insights came from refracturing the older, vertically drilled Barnett Shale wells.

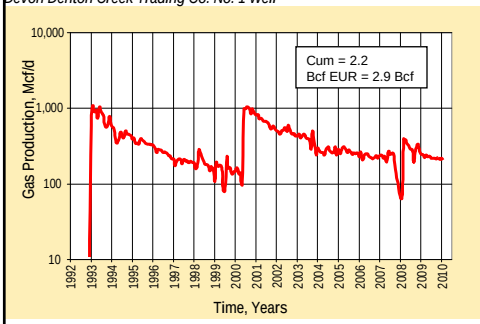
- Recognized that the second (or third refracture) was contacting additional shale reservoir.
- The refracs of older wells increased gas reserves to over 2 Bcf/well. (Subsequent refracs of more modern, more efficiently completed wells added about 0.5 to 0.6 Bcf per refrac.)

This provided the evidence that it was possible to create sufficiently permeable flow paths in deep gas shales.

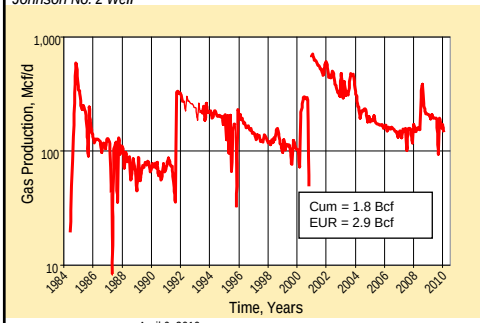
Refracturing Previously Stimulated Shale Wells

Barnett Shale/Newark East Field

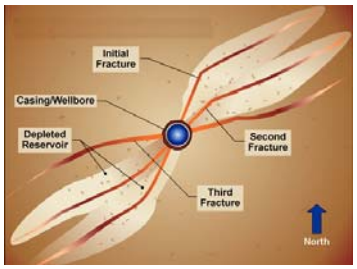
Devon Denton Creek Trading Co. No. 1 Well



Johnson No. 2 Well



Fracture Reorientation



Performance of Refraced Wells

The Denton Creek Trading #1 well became the "poster child" for the refrac program and the recognition that one could "create a permeable gas shale reservoir":

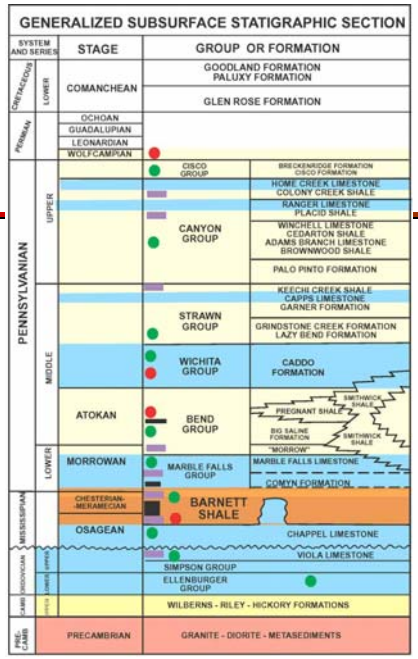
- The well was drilled in late 1992 and was completed from 7,738' to 8,007'. It was stimulated with a large frac containing 789,000 gal water and 1,548,000 lb sand.
- From late 1992 through early 2000 (6 years), the well recovered 0.8 Bcf, was producing 140 mcfd, and had an EUR of 1.0 Bcf.
- In 2000, the well was refractured, restoring the gas rate to 1,000 Mcfd; since the refrac, the Denton Creek Trading # 1 well has produced an additional 1.4 Bcf and has an EUR of 2.9 Bcf.

Performance of Refractured Barnett Shale Wells* (1999-2000 Program)

	Well Name	Date	Original Stimulation (Bcf)		After Refracture (Bcf)		Increased Recovery (Bcf)
			Cum Recovery**	EUR	Cum Recovery***	EUR	
1	Denton Creek #1	1992	0.8	1.0	2.2	2.9	1.9
2	Talley #1	1993	0.4	0.5	2.6	4.0	3.5
3	Logan #2	1991	0.4	0.6	2.2	3.3	2.7
4	Ted Morris #1	1992	0.6	0.8	2.1	3.0	2.2
5	Johnson #2	1984	0.3	0.4	1.8	2.9	2.5
	Average			0.7		3.2	2.5

**Based on analysis by Advanced Resources.*
***Cumulative gas recovery at date of refrac.*
****Cumulative gas recovery as of April 2008*

4. Overview of Exploration, Reservoir Characterization and Development

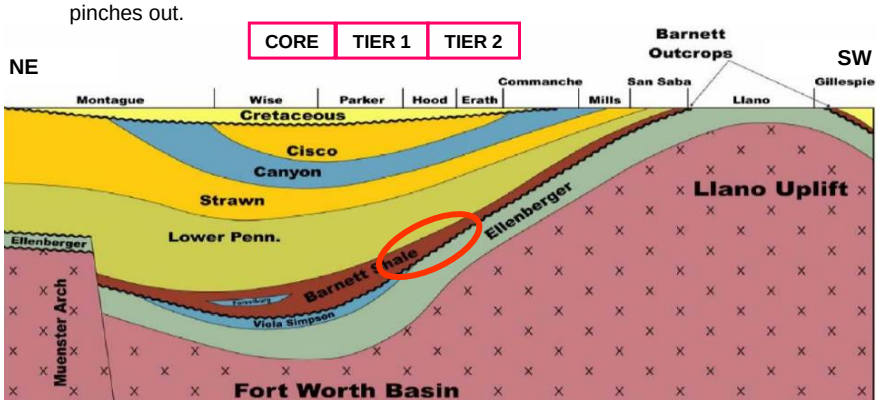


Bend Arch - Fort Worth Basin: Stratigraphic Column

- Mississippian-age, organic-rich shale,
- Unconformably overlies Ordovician Ellenburger Group limestone,
- Overlain by Pennsylvanian Marble Falls Fm.

Barnett Shale – NE to SW Cross Section

Cross-sectional view of the Barnett Shale shows Core Area in Wise & Parker Counties has thicker, deeper Barnett Shale. Thick Viola Simpson frac barrier protects against the wet karstic Ellenburger limestone. The Barnett Shale becomes thinner and shallower into Tiers 1 and 2, while Viola frac barrier pinches out.



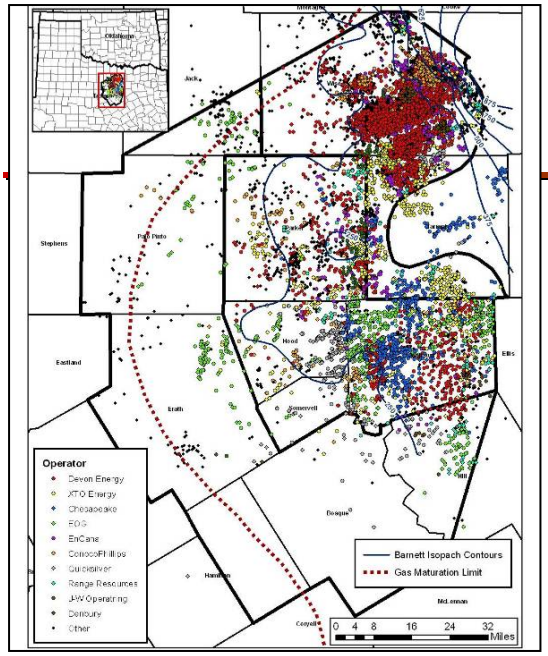
More Rigorous Definition of Gas In-Place

In 1999, a major effort was launched to define the resource concentration of the Barnett Shale:

- Two Upper and Lower Barnett conventional cores of 90' and 60'
- Two 10' pressure cores in Lower Barnett

This established a much larger gas in-place and significantly changed the development strategy for the Barnett Shale.

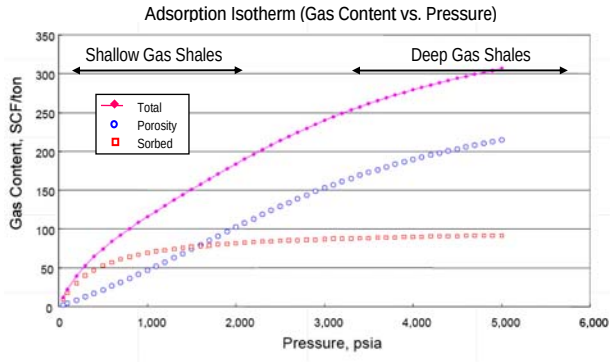
	Original Values	Updated Values
Pay Interval	Lower Barnett Only	Upper and Lower Barnett
Porosity	3.7%	4.5% to 6%
Water Saturation	50 to 60%	25%
Adsorbed Gas	Fixed	Related to TOC
GIP (Bcf/mi^2)	53	145



Mapping of Barnett Shale Thickness

- Barnett Shale is thickest in the deep Core Area (up to 900 feet thick).
- About 200 ft thick in Parker and Hood Counties (Tier 1).
- Less than 100 ft thick further west.
- Shale thickness correlates with gas in place and per-well recoveries.

More Rigorous Definition of Gas In-Place



Free Gas. The more rigorous characterization of the Barnett Shale increased gas filled porosity (free gas) by two-fold.

Adsorbed Gas. The pressure core showed that gas stored by adsorption was 120 scf/ton in the rich (5.2% TOC) Lower Barnett compared to an earlier estimate of 42 scf/ton.

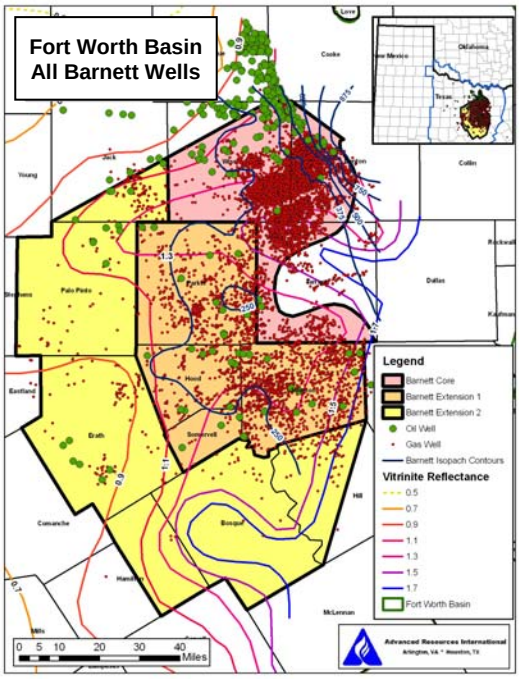
Better Understanding of Thermal Maturity

Initially, due to less favorable gas production from lower thermal maturity areas, development was restricted to areas with vitrinite reflectance (Ro) values (cuttings-based) of 1.4 or greater, limiting the prospective areas.

Subsequent assessments showed that the Ro value in cores was typically 0.2 greater than in cutting, helping expand the prospective area.

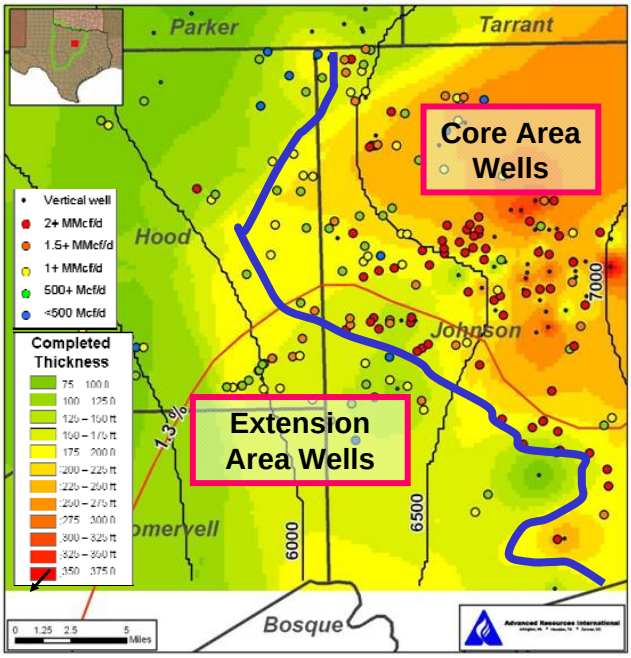
Better understanding of the maturation of the Barnett Shale helped lower the Ro cuttoff value to 1.15 to 1.25 (from core) greatly increasing the prospective area.

Further analysis also showed that many of the early well failures in the lower Ro areas were due to lack of fracture containment rather than insufficient thermal maturity.



Barnett Shale Thermal Maturity

- Maximum thermal maturity in Core Area (Ro = 1.5%).
- Barnett Shale becomes oil-prone below Ro = 1.15%.
- Thermal maturity declines to the north and west.
- Efforts are underway in the thick, lower Ro areas to the north to develop a combination shale oil and shale gas play.



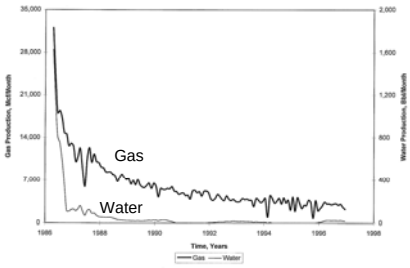
Barnett Shale Play Boundaries

- Well productivity changes rapidly due to geology.
- Core Area is deeper, thicker and higher maturity with EURs of over 2 Bcf/well.
- Extension Area wells are thinner, shallower and lower maturity with EUR's of less than 1.5 Bcf/well.

5. Assessing Improving Well Performance

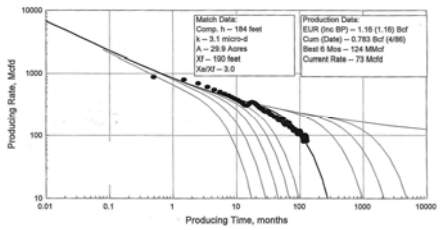
Well #3 Production History

4 Stella Young, Wise Co., TX



Well #3 Type-Curve Match

4 Stella Young, Wise Co., TX



Source: Advanced Resources International, 1998

Assessment of Well Performance

Early assessment of Barnett Shale well performance, using a two layer reservoir model (including a thin, high permeability zone as the flow path and a thick, essentially impermeable, shale interval), established the "mind-set" that the hydraulic fractures were long (1,200 feet) and the drainage area was large (320 acres/well).

Reassessment of Barnett Shale well performance established that actual fracture lengths were much shorter on the order of 200 feet, and the drainage area per well was limited to 15 to 30 acres, leading operators to reconsider their well spacing strategies.

Initial Barnett Shale Well Performance

The initial vertical wells, drilled into the Barnett Shale during 1985 to 1990, provided only modest reserves of 0.4 to 0.5 Bcf/well.

The introduction of high volume "slick water", low proppant concentration stimulations, plus adding the Upper Shale interval, increased reserves to 0.8 to 1.0 Bcf/well.

	Well	Completion Interval, ft	Cum. Prod., Bcf*	EUR, Bcf	Drainage, Acres	Fracture wing, ft
A. Initial 74 wells (1985-90)						
Type well	1	7,558-7,733	0.32	0.39	11	115
Type well	2	6,943-7,133	0.38	0.51	13	95
Special well	3	6,884-7,080	0.78	1.16	30	190
B. Subsequent 217 well (1991-96)						
Type well	4	7,300-7,528	0.62	0.94	21	160
Type well	7	7,514-7,746	0.33	0.83	14	195

Source: Advanced Resources, 1998
*As of mid- 1997

Barnett Shale Core Area: Modern Day Well Performance

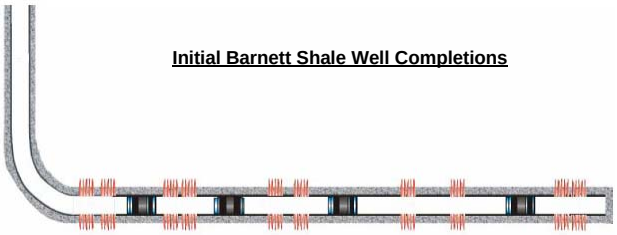
The introduction of horizontal wells increased well performance by about three-fold. Recent well performance has been declining as operators are "stepping out" into lower quality portions of the maturing Core Area.

	Successful Vertical Wells		Successful Horizontal Wells	
	(# Wells)	(Bcf/w)	(# Wells)	(Bcf/w)
1990-1995	215	2.3*	1	5.1
1996-2000	500	1.7*	3	1.2
2001-2003	2,001	1.3	76	3.2
2004-2006	904	1.0	1,008	2.8
2007-2008	131	0.6	1,810	2.4

*Includes improved performance from refracs.

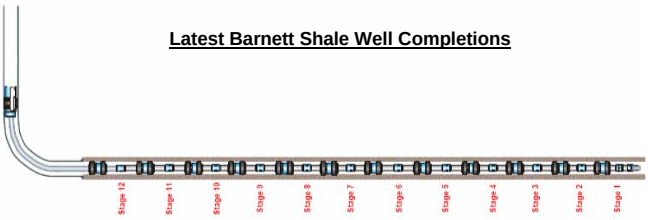
Lower Damage, More Effective Horizontal Well Completions Provide Higher Reserves Per Well

Initial Barnett Shale Well Completions



Cased, Cemented, Perforated and Isolated Horizontal Wellbore

Latest Barnett Shale Well Completions

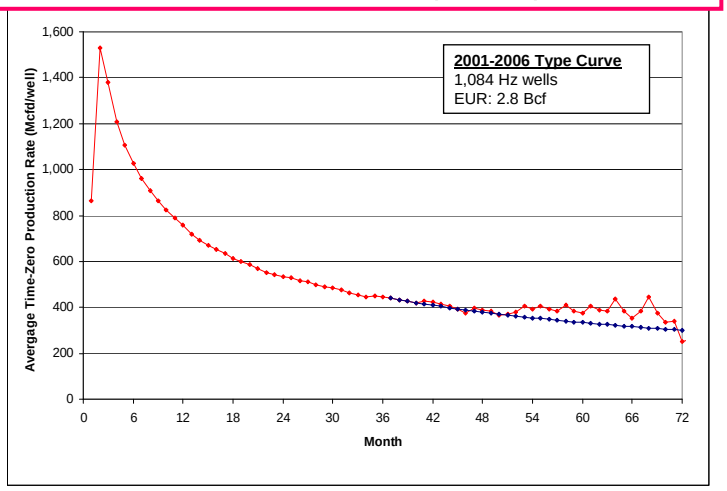


A 12 Stage Open Hole Completion System Using Open Hole Packers for Mechanical Diversion

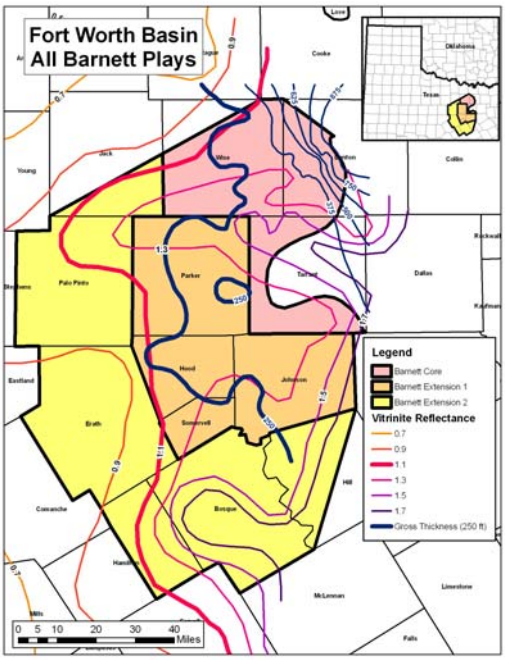
*Typically 18,000 barrels of water and 400,000 pounds of sand per stage

Horizontal Well Production "Type Curve"

Barnett Core Area Hz Wells (2001-2006)



6. Lessons Learned



Lesson #1. High-Quality Resource Areas Provide the Essential Foundation for Success

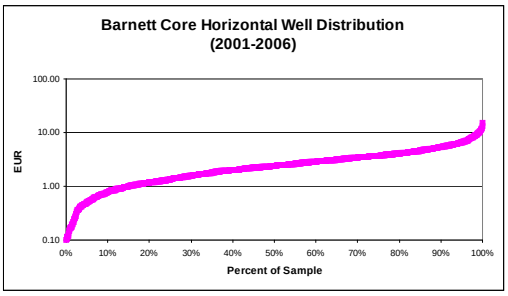
The Core Area of the Barnett Shale with 150 Bcf/mi^2 starts out with an inherent advantage over the extension areas with much leaner 50 Bcf/mi^2 resource concentration.

Similar high and low resource concentration areas exist in each of the gas shale plays we have evaluated.

Barnett EUR Distribution

Barnett Core Horizontal

2001-2006	Successful Wells	EUR/Well (Bcf)	Range	
			Low Value (Bcf)	High Value (Bcf)
10%	108	7.3	5.4	15.1
20%	217	4.2	3.4	5.4
30%	325	2.7	2.0	3.4
40%	434	1.2	0.1	2.0
Total	1084	Avg.		
dry holes	43			
Well Count	1127			
Success Rate	96%			

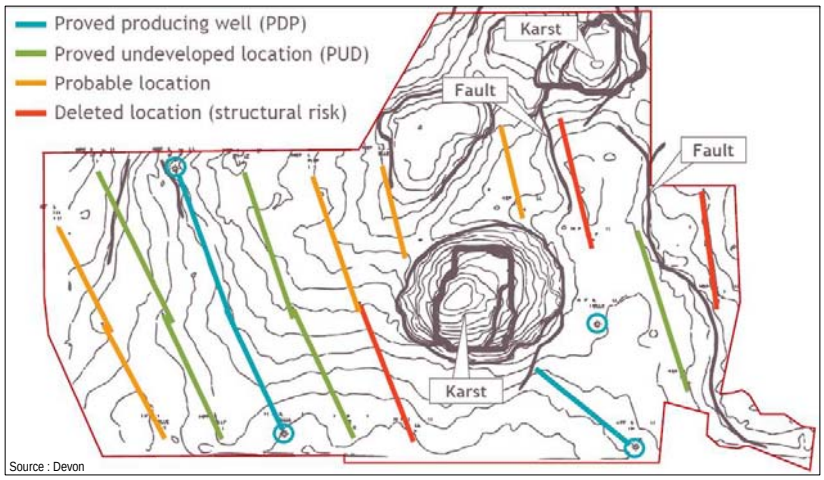


Lesson #2. Even in High-Quality Resource Areas, Individual Well Performance Will Vary Greatly

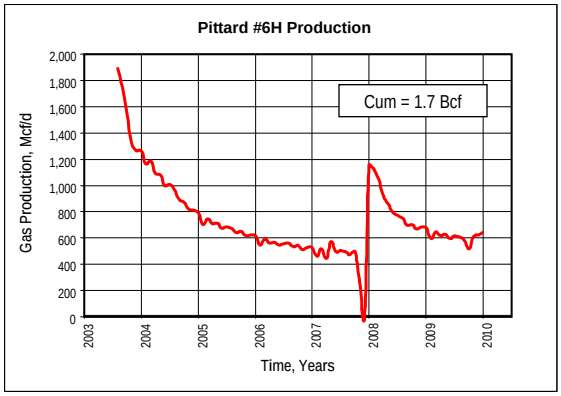
A detailed look at over 1,000 horizontal wells drilled between 2001 and 2006 in the Core Area shows considerable variations in well performance:

- The statistical average well in the Core Area has an EUR of 2.8 Bcf.
- The best 10% of the wells in the Core Area have EUR/well of over 7 Bcf.
- The lowest 40% of the wells in the Core Area have EUR/well of only 1.2 Bcf.
- A small number, 43 wells (4%) are “dry” (non-productive)

Lesson #3. 3D Seismic is Widely Used in the Barnett Shale to Avoid Faults and Karsts



Lesson #4. Horizontal Barnett Shale Wells May Also Benefit from Refracs



Operators have achieved success with refracturing lower performing shale wells located in otherwise geologically favorable areas.

The Pittard #6H horizontal well was refracced in late 2007, more than doubling its gas production rate.

Lesson #5. Directional and Horizontal Drilling Is Key to Urban Barnett Shale Development

The Barnett Shale underlies much of the Dallas/Ft. Worth area.

Source : Carrizo

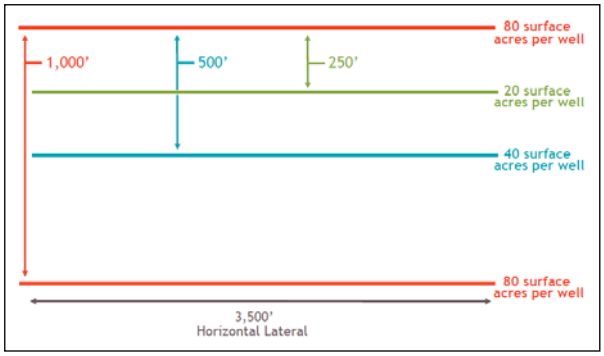
Lesson #6. We Have Not Yet Solved the Issue of Optimum Barnett Shale Well Spacing

Given the rich concentration of gas in-place in the Barnett Shale, operators are still examining the topic of optimum well spacing.

- The most common field design is to drill two 2,500' laterals per section, spaced 1,320' apart (80 acre/well).
- Some operators are drilling one longer lateral of 3,500' to 4,000' feet per section, spaced about 1,000' apart (80 acre/well).
- Currently, 80 acre/well spacing is providing 15 to 20% recovery of GIP.
- Closer well spacings of 40 acres/well could increase recovery of GIP by 10 to 15% but at lower incremental reserves per well.
- Pilot efforts are underway testing well spacing of 20 acres/well to raise overall gas recovery to over 50% of GIP.

Optimum Well Spacing (Operator A)

Alternative Well Spacing Designs



Source: Devon Energy (2009)

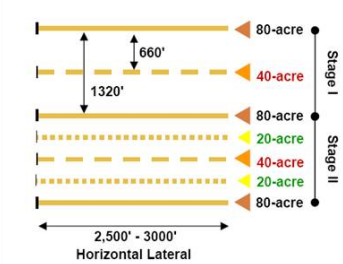
Performance of Closer Spaced Wells

- 80 acres per well (1,000' apart)
  - 187 wells online (2.5 Bcf per well)
- 40 acres per well (500' apart)
  - 57 wells online (2.3 Bcf per well)
- 20 acres per well under study

Optimum Well Spacing (Operator B)

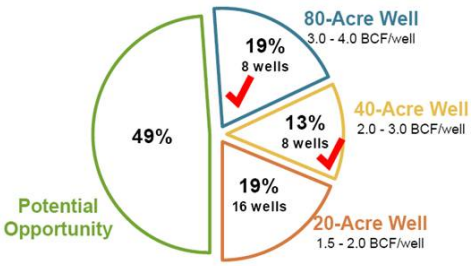
- Initial development on 80 acre well spacing will recover only a modest (19%) fraction of gas in-place.
- Downspacing to 40- and 20-acre would increase the recovery of gas in-place to over 50%, although well performance would decline.

Drilling Spacing Diagram



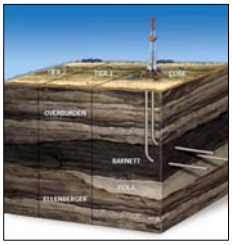
Recovery of Natural gas

GIP 150 Bcfe per 640-acre section



Source: XTO (2009)

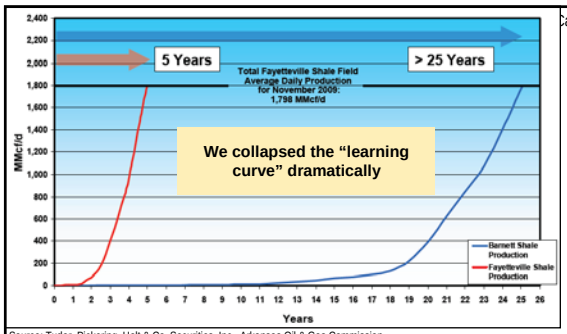
6. Concluding Thoughts



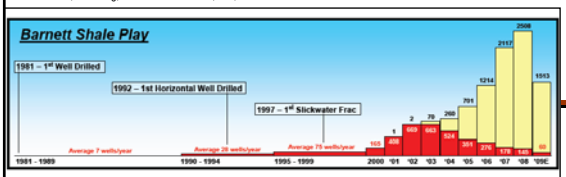
The Barnett Shale opened up a new class of natural gas resources by demonstrating that:

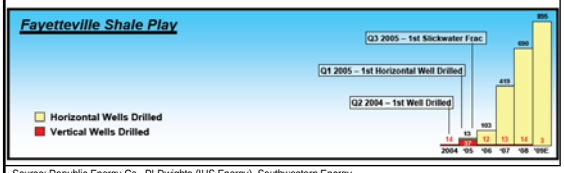
- Shale gas source rocks can have high gas storage capacity – 100 to 200 Bcfe / mi^2.
- Extremely low permeability shales can be unlocked using horizontal drilling and massive hydraulic stimulation.

These breakthroughs have enabled the Barnett Shale to become the largest natural gas field in the U.S.



Source: Tudor, Pickering, Holt & Co. Securities, Inc., Arkansas Oil & Gas Commission





Source: Republic Energy Co., PI-Dwights (IHS Energy), Southwestern Energy

The Barnett Shale "Lessons Learned" Helped Compress the Development Pace of the Fayetteville Shale

6. Concluding Thoughts

Today's active pursuit of deep gas shales - - the Fayetteville, Marcellus, Haynesville and Horn River shales in North America and the numerous gas shales in China and other countries - - could make gas shales the largest undeveloped natural gas resource in the world.

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